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**REMOTE SENSING:
SNOW MONITORING TOOL FOR
TODAY AND TOMORROW**

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MARCH 1977



**GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND**

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REMOTE SENSING: SNOW MONITORING TOOL FOR TODAY AND TOMORROW¹

By

Albert Rango²

Introduction

Remote sensing has been described as the measurement or acquisition of information on some property of an object (in this case snow), by a recording device not in physical contact with the object under study. This can include the use of spacecraft as well as instruments mounted on "cherry-pickers" above the snow surface. Remote sensing is not to be confused, however, with the telemetry of conventional measurements acquired in remote regions, sometimes automatically. This separate method of data collection and relay can be used together with remote sensing methods to provide timely receipt of snow information.

Certain advantages are associated with remote sensing of snow. Data can be easily obtained from remote regions where conventional access is difficult or restricted, including wilderness areas. Remote sensing can acquire data over large areas at considerably less cost than conventional ground measurements over the same regions. At the same time the remote sensing techniques can be used to supplement and extrapolate conventional point data over wide areas.

Various types of remote sensing are now available or will be in the future for snowpack monitoring. Aircraft reconnaissance is now used in a conventional manner by various water resources agencies to obtain information on snowlines, depth, and melting of the snowpack for forecasting purposes. The use of earth resources satellites for mapping snowcovered area, snowlines, and changes in snowcover during the Spring has increased during the last five years. Gamma ray aircraft flights, although confined to an extremely low altitude, provide a means for obtaining valuable information on snow water equivalent. The most recently developing remote sensing technology for snow, namely, microwave monitoring, has provided initial results that may eventually allow us to infer snow water equivalent or depth, snow wetness, and the hydrologic condition of the underlying soil.

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Presently Available Remote Sensing Techniques

Aircraft Reconnaissance. — Photography taken from the air with various types of camera systems can provide an adequate display of certain areas covered by snow from which the snowline elevation can be derived. From the more common low altitude flights the objective is to locate the snowline and from that infer the total watershed snowcovered area. Because earth-oriented vertical photos from low altitude only cover relatively small areas, much of the photography is taken at oblique angles. Such photography has locational problems and this limits the approach to general snowcover estimates. As the aircraft altitude is increased, larger areas come into the field of view of the cameras and snowcover over increasingly large watersheds can be mapped. Even from the altitude of the NASA U-2 (60,000 ft or 18.3 km), however, mosaicking of five photographs is required to cover a watershed 187 mi^2 (484 km^2) in area. This is very time consuming and makes timely interpretation difficult.

Another approach, using low altitude aircraft flights, makes use of a previously drafted watershed base map and a snowcover observer such as used by the Arizona Salt River Project (Warskow, Wilson, and Kirdar, 1975). Using this method the observer records the location of the snowline on the base map as he flies over pre-selected ground areas. At the same time he may make estimates of snow depth and melting condition of the snowpack based on the appearance of ground features. After returning to the office the data are worked up into a snowcovered area map, usually at 1:1,000,000 scale. Associated with this type of aerial survey is the use of aircraft to observe snow depth markers. The aerial markers are placed in certain index areas and the data collected are used to supplement ground snow survey data. The markers are observed from a slow flying, low altitude aircraft. The depth can be recorded directly on a chart furnished to the aircraft observer, or a photograph of the marker can be taken from the airplane and later enlarged and the depth data extracted. Density values are assigned to the markers on the basis of nearby snow course measurements for the purpose of estimating the snow water equivalent at the marker. An excellent description of the use of aerial snow markers is given by Peterson (1977).

As with any snow measurement technique, certain advantages and disadvantages are associated with aircraft reconnaissance. On the positive side, a flight can be flown whenever conditions are good or a break in the weather occurs; supplemental data on watershed conditions can be obtained from low altitude flights; and the use of index areas is amenable to airborne surveys. On the negative side, however, low altitude aircraft flights can be dangerous and lives have been lost; they are weather dependent; not all areas of the snowpack can be surveyed and some views are necessarily oblique; the flights are expensive; and changes of observers cause inconsistencies in observations and introduce variability in the data.

Satellite Snowcover Observations. — In contrast to low altitude observations, views from satellites provide an extremely good perspective, especially if resolution on the order of 80 m (like that from Landsat) is available. Using the satellite photographs directly is the least complex method for determining the percentage of watershed covered by snow. The snowline can be delineated directly on the satellite imagery (at 1:1,000,000 scale in the case of Landsat), and the area covered by snow is then planimetered inside the watershed boundary. More sophisticated analysis of images involving enlargements, zoom transfer scopes, gridded imagery, and density slicing are discussed by Rango and Itten (1976). Further sophistication and detail can be obtained by working directly with the satellite computer compatible tapes in digital analysis. On an interactive computer system with a trained analyst, it is possible to detect snow in trees, separate snow from clouds, locate melting snow areas, and superposition snowcovered area and various watershed elevation zones.

Various satellites are available that can produce images and/or tapes for use in extracting snowcovered area data with the above mentioned techniques. These satellites include:

1. Landsat - possessing two visible and two near infrared observing bands, resolution about 80 m, coverage every nine days clouds permitting (two satellites in use), and data available within 2-7 days after acquisition.
2. NOAA satellites (with the Very High Resolution Radiometer [VHRR] and Visible and Infrared Spin Scan Radiometer [VISSR]) - one visible and one thermal infrared band, resolution about 1 km, coverage every day clouds permitting, and data available within 1-3 days after acquisition.

It has been observed by Barnes and Bowley (1974) that even though more detailed patterns can be identified in U-2 aircraft data, the effective information content of the Landsat image with regard to mapping snowcover is equal to that of the higher resolution photography. It was also apparent that snowline determinations from Landsat were considerably easier to obtain than from the U-2. In regard to this observation, Wiesnet and McGinnis (1974) indicate that Landsat snow mapping is six times faster than U-2 snow mapping.

NOAA-2 VHRR snow mapping is almost as fast as Landsat, more timely, and applicable on large watersheds. Wiesnet and McGinnis (1974) derived a cost-comparison figure for NOAA-2 satellite measurements of Sierra Nevada snowcover versus conventional aircraft measurements. Assuming that 20 basins were of interest and that a simple altimeter survey by light plane was possible, at least 40 hours would be required at a total cost of at least \$20,000. Using satellite data, the entire Sierra block could be mapped in two man-days for a

direct cost of about \$100. Thus the comparative cost ratio is 200:1 in favor of the satellite, recognizing, of course, that the costs of the plane and the satellite were not included.

It has become evident that snowcovered area measurements from Landsat and, in certain cases, NOAA VHRR are adequate for the mapping of watershed snowcover. Satellite determinations of snowcover have in fact replaced similar conventional aircraft determinations in certain watersheds, such as the Salt River watershed in Arizona. Advantages of using satellite derived snow extent as opposed to aerial surveys include the following: (a) satellite mapping is less expensive and faster; (b) large areas can be surveyed at once; (c) acceptable accuracies are achieved, partially as a result of the fact that snow is easily detected, and that a relatively constant viewing perspective is available repetitively; and (d) the satellite techniques are infinitely safer. The major disadvantage is that over small watersheds high resolution spacecraft, such as Landsat, have a limited frequency of observation that can be decreased even further by poor weather conditions. Additionally, only snowcovered area data is now available operationally from satellites, whereas aerial surveys supply more supplemental information.

Gamma Ray Detection. — The use of natural background terrestrial gamma radiation to measure snow water equivalent was first developed in the 1960's at about the same time by the Norwegians and the Russians. Since then it has been tested extensively in the United States and Canada (Bissell, 1975). The concept of the monitoring system is based on the theory that the mass of water between the source (ground) and the detector (on an aircraft) will attenuate the natural gamma emission of the ground proportional to the amount of water (snow). If the gamma emission of the soil can be measured or inferred, then the snow water equivalent can be calculated. Although this method can cover more extensive areas than conventional point measurements can and thus be used to extend the applicability of the conventional data, there are some serious limitations. First, the aircraft employed must fly at extremely low altitudes (about 150 m) to minimize attenuation of the gamma rays. As a result, areas to receive coverage must be chosen carefully and be used as index areas for larger regions. In addition, the flights are restricted to flat or gently rolling topography because of the low altitude requirements and the fact that mountainous terrain and its geometric variability causes serious data interpretation problems. This means that this technique is not very applicable to the heavy snowpacks of the mountainous western United States.

Currently the gamma radiation method is being used in Canada and the United States semi-operationally. In 1976 NOAA flew gamma ray instrumentation to assess the flood potential of the Spring snowpack in Souris River Basin in

North Dakota. In 1977 the U. S. Army Corps of Engineers and NOAA used the technique to measure the severe snow buildup in New York near the Great Lakes.

Quasi-Operational Satellite Snowcover Test. -- NASA instituted Applications Systems Verification and Transfer (ASVT) programs to demonstrate and test the usefulness of the developing technology in earth resources. Because results from satellite snow mapping and runoff correlation have been encouraging, a project on the Operational Applications of Satellite Snowcover Observations (OASSO) was instituted as part of the ASVT program in cooperation with six Federal (Soil Conservation Service, Bureau of Reclamation, Geological Survey, National Oceanic and Atmospheric Administration, Bonneville Power Administration, and the Corps of Engineers) and three state (Arizona Salt River Project, Colorado Division of Water Resources, and the California Department of Water Resources) agencies. This project is described in detail in NASA SP-391 which is the proceedings of the first OASSO Workshop (Rango, 1975). In addition, a Handbook of Techniques for Satellite Snow Mapping was developed for use by the OASSO participants (Barnes and Bowley, 1974). The participants are now in the third year of the four year test. They have acquired most necessary satellite snow mapping expertise and are now testing the use of the snowcover data in operational forecast techniques. Results to date have shown that snowcovered area information can be used to improve forecast updates throughout the snow-melt season, either through typical regression approaches or models. The conclusion of the project in early 1979 will include a final workshop, widespread dissemination of results through reports and journal articles, and a companion cost/benefit study.

Research and Development

A variety of remote sensing systems for snow measurements are under development in several NASA programs. Various improvements are being contemplated for the Landsat series of spacecraft. In 1978, Landsat-C will have a thermal infrared sensor with a spatial resolution of about 240 m. Combined with the near infrared sensors, the thermal infrared band should permit delineation of the areas of the snowpack undergoing snowmelt. In addition, a single Return Beam Vidicon camera on Landsat-C will produce imagery with a resolution of 40 m. Landsat-D will be launched in the 1980-1981 time frame with a new multispectral instrument called the thematic mapper that will provide resolutions of about 30 m in the visible and near infrared and 120 m in the thermal infrared. A 1.55-1.75 μ m near infrared band will be added for improved discrimination of snow and clouds. Late in the 1980's a high resolution geostationary satellite permitting high frequency observations is a possibility.

Microwaves. — Sensors operating in the region of the electromagnetic spectrum bounded on the short wavelength side by the far infrared (at 1 mm) and on the long wavelength side by very high-frequency radio waves are sensitive to microwave energy. Microwaves are emitted by the earth's surface and other natural objects such as snow. Depending on the actual wavelength of the sensor, the observed radiation can come from the soil, snow, or be reflected from the sky. The objective when using passive microwave radiometers (Figure 1) is to measure the microwave emission and infer the characteristics of the snowpack. The use of radiometers at several wavelengths may be necessary to separate the emission of the snow from the soil. It has been found that microwave emission of the snow changes considerably when melt water is present.

Our initial experiments with passive microwaves and snow have focused on aircraft flights with a multispectral radiometer package flown at 2000-3000 ft (610-915 m) over experimental snow fields at Steamboat Springs and Walden, Colorado and near the Central Sierra Snow Lab in California. In this early stage of experiments attempts are being made to develop a method that will first determine differences between shallow and deep snow fields (a valuable adjunct to just the sensing of snowcovered area) and also between dry and wet snowpacks. Further data collection and analysis plus modeling efforts will be directed toward quantification of snow water equivalent, depth, structure, temperature, and liquid water content. Results from initial analysis of 1976 flight data indicate that meaningful qualitative differences can be detected as shown in Figure 2. In addition, the condition of the underlying soil surface can also be inferred which directly affects runoff prediction. A second year of flights was completed during the Winter of 1977.

An associated series of measurements is being performed with active microwave sensors (radar) both in Colorado and California. These sensors are ground based, some mounted on 80 ft (24 m) booms above the snow, that send out signals and measure the reflected microwave return signal. These experiments are complementary to the passive microwave experiments and are also directed toward inferring snowpack characteristics remotely. It should eventually be possible to fly such radar systems on satellites and measure snow water equivalent from space with a reasonably high resolution.

Future Space Applications. — Visible and infrared systems will provide improved resolution data in the next few years, but to insure a fully operational product, frequency of coverage must be increased to at least once every 3-6 days. Data delivery must also improve so that products are received within 48 to 72 hours of data acquisition. The applicability of the visible and infrared data for snow mapping, however, has been firmly established and should be easily adopted by most user agencies.

Microwave sensors will hopefully be developed during the next ten years because they have great potential for sensing snow volume. Space-based passive systems which provide wide area coverage of snowcover are possible and will be most applicable over flatland areas such as the high plains because of low resolution capabilities (10-25km). Experimental analysis of the Nimbus satellite Electrically Scanning Microwave Radiometer (ESMR) data over several United States and Canadian high plains snowpacks for 1975-1976 is now underway. Active microwave systems in space will be best suited for obtaining measurements on small watersheds and in small mountain clearings where high resolution (25-100 m) is required. Because the active systems will not cover all snowpack areas, the instruments would probably be pointable for coverage of pre-located study areas. An ultimate operational system would provide data on snowcovered area, snow volume, and snowpack condition using remote sensing techniques. Snow information could then be acquired routinely from wilderness preserves, entire watersheds, or index areas in a rapid and timely fashion.

The Snow Surveying System of the 1990's

Based on past snow survey, snow hydrology research, and remote sensing experience, the following prognostication is presented to provide a point of departure for discussion of how remote sensing will be combined with conventional snow measurements in the future.

Ground Measurements. — Conventional snow survey measurements will continue to be made with increasing automation of many sites. In addition to meteor burst data relay, the use of satellite data collection systems will find greater use for transmitting snow data. These conventional snow survey measurements will be the cornerstone of the snow runoff forecasting program, but a shift in emphasis in the use of the data will occur. First, rather than the data almost exclusively being used in regression forecasts, input to snowmelt runoff models will predominate. The fact that automation will allow more frequent measurements will promote the use of these models. Secondly, the conventional ground data will be used to calibrate the remote sensing data which will then be used to extrapolate the point data over large areas. New instruments for snow measurements, currently being developed by the U.S. Forest Service, NASA, and the California Department of Water Resources, will be adapted to use at the automated sites. These instruments will permit better measurement of water equivalent, snowpack density profiles, and profiles of liquid water content. Such data will have direct pertinence for input to the shorter duration forecast models.

Aircraft Measurements. — Low altitude gamma ray flights will be concentrated over plains areas and permanent flight lines will be surveyed every year. Selected areas will be surveyed on an irregular basis depending on flooding potential. Only limited use of this method will take place in the mountainous West with helicopters playing a significant role.

Low and high altitude aircraft flights over all areas for snowcover mapping will be drastically curtailed in lieu of increased satellite coverage and reliability. The satellite data will be used to plan selected aircraft flights in especially critical runoff situations.

In mountain snowpack areas multispectral passive microwave radiometer systems will be flown at several thousand feet to obtain water equivalent and liquid water data over small watersheds and pre-selected flight lines. These data will be used to extend the ground-based data and also to supplement data from active microwave satellite systems. These aircraft-mounted passive microwave systems may also find applications in non-mountainous snow areas because of the capability for assessing the hydrologic condition of the underlying soil.

Satellite Measurements. — High resolution, geosynchronous earth resources satellites with visible and infrared sensors will provide the potential for near continuous, operational coverage of snowcovered area with delivery of data to users in 48-72 hours. The processed data will most likely come from regional data centers where computer programs will convert the satellite data into watershed snow extent maps. The maps will be available to all water and energy agencies and will be verified and calibrated when necessary by a small number of light aircraft flights in various regions of the country. Additional information on melting areas and snow albedo will be available.

Active microwave radar systems will eventually be mounted on polar orbiting satellites for coverage of western U.S. snowpack areas with resolutions of about 25-100 m. This will permit measurements of the snowpack in forest clearings and numerous points across a watershed for translation to large area water equivalent and liquid water data. Frequency of coverage will be every 7 days, and because clouds will not interfere, this coverage will be assured. Snowpack characterization will be available over large areas and transmitted to users in 48-72 hours. It is most likely that the data acquired from space will provide a best estimate range of water equivalent and liquid water, and ground data will be used to calibrate and quantify the satellite data.

Passive microwave systems in space will provide large area water equivalent and liquid water coverage of the snowpack every 5 days over non-mountainous areas where low resolution data is not a serious drawback. Clouds will not reduce this frequency of coverage, and calibration will be provided by scattered ground measurements and aircraft gamma ray flights over established flight lines. These data will also be available in 48-72 hours.

Integration of the data from this multisensor, multilevel system will be accomplished at regional data processing centers. The centers will produce

snow extent maps coupled with similar maps of snow water equivalent or depth and liquid water content. The regional centers will either produce model-derived forecasts of runoff or supply the data to the appropriate agencies by facsimile or teletype for forecast purposes in 2-3 days after acquisition. The actual ground, aircraft, and satellite data will be available to the agencies upon request.

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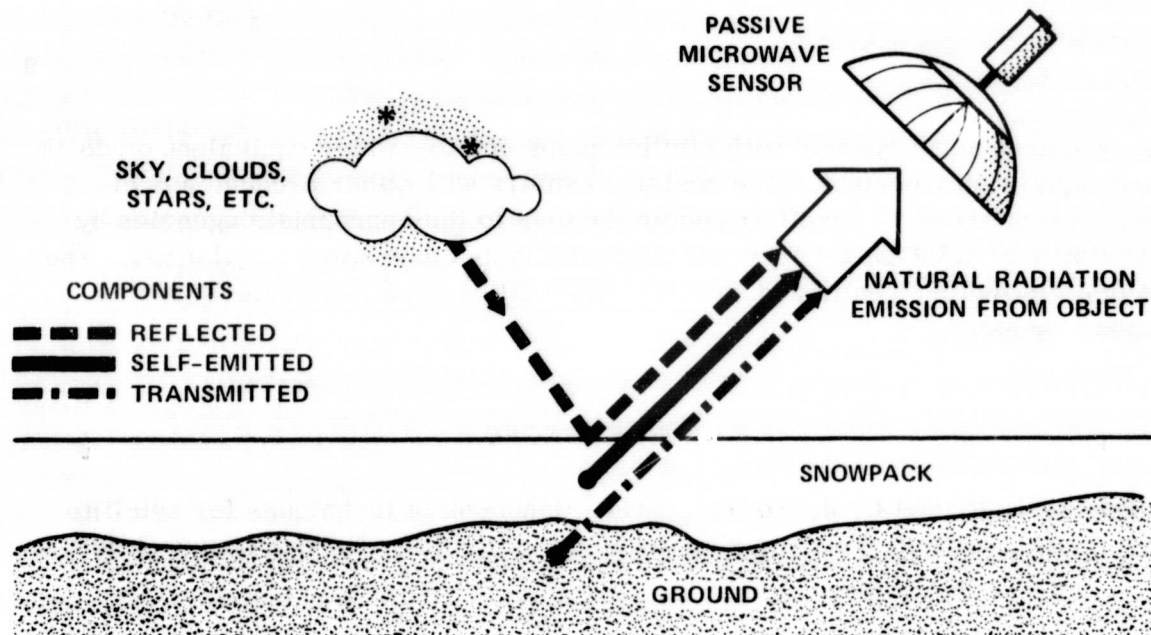


Figure 1. Natural Microwave Radiation Emanating from Snow

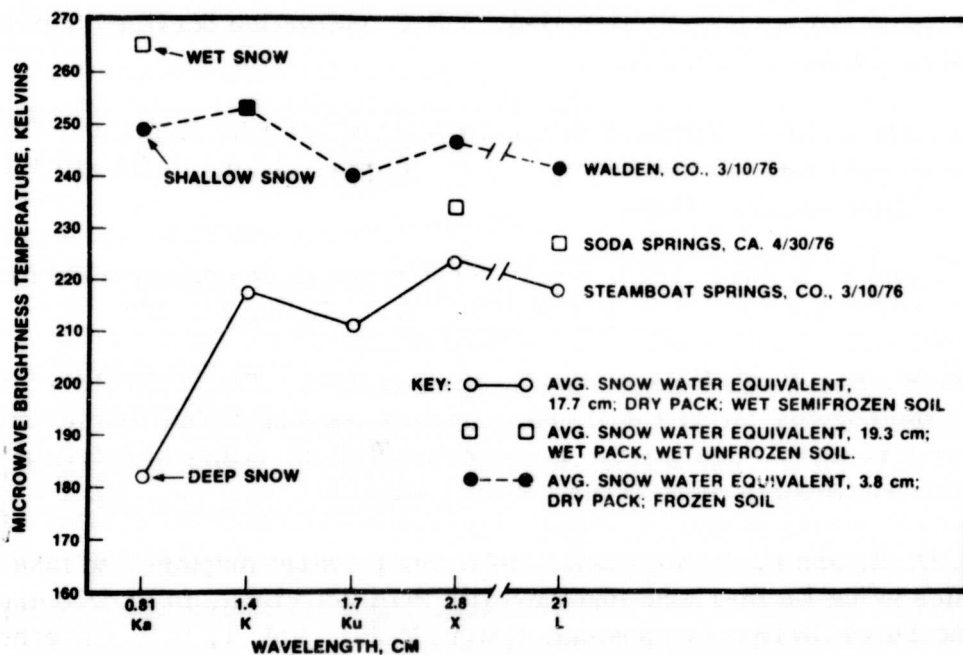


Figure 2. Variation of Microwave Brightness Temperature with Radiometer Wavelength for Snow in 1976